ELECTRICAL RESISTIVITY TECHNIQUES FOR SUBSURFACE INVESTIGATION

Steve Cardimona

Department of Geology and Geophysics, University of Missouri-Rolla, Rolla, MO

ABSTRACT

Geophysical resistivity techniques are based on the response of the earth to the flow of electrical current. With an electrical current passed through the ground and two potential electrodes to record the resultant potential difference between them, we can obtain a direct measure of the electrical impedance of the subsurface material. The resistivity of the subsurface, a material constant, is then a function of the magnitude of the current, the recorded potential difference, and the geometry of the electrode array. Depending upon the survey geometry, the data are plotted as 1-D sounding or profiling curves, or in 2-D cross-section in order to look for anomalous regions. In the shallow subsurface, the presence of water controls much of the conductivity variation. Measurement of resistivity is, in general, a measure of water saturation and connectivity of pore space. Resistivity measurements are associated with varying depths relative to the distance between the current and potential electrodes in the survey, and can be interpreted qualitatively and quantitatively in terms of a lithologic and/or geohydrologic model of the subsurface.

INTRODUCTION

Geophysical resistivity techniques are based on the response of the earth to the flow of electrical current. In these methods, an electrical current is passed through the ground and two potential electrodes allow us to record the resultant potential difference between them, giving us a way to measure the electrical impedance of the subsurface material. The apparent resistivity is then a function of the measured impedance (ratio of potential to current) and the geometry of the electrode array. Depending upon the survey geometry, the apparent resistivity data are plotted as 1-D soundings, 1-D profiles, or in 2-D cross-sections in order to look for anomalous regions.

In the shallow subsurface, the presence of water controls much of the conductivity variation. Measurement of resistivity (inverse of conductivity) is, in general, a measure of water saturation and connectivity of pore space. This is because water has a low resistivity and electric current will follow the path of least resistance. Increasing saturation, increasing salinity of the underground water, increasing porosity of rock (water-filled voids) and increasing number of fractures (water-filled) all tend to *decrease* measured resistivity. Increasing compaction of soils or rock units will expel water and effectively increase resistivity. Air, with naturally high resistivity, results in the opposite response compared to water when filling voids. Whereas the presence of water will reduce resistivity, the presence of air in voids should increase subsurface resistivity.

Resistivity measurements are associated with varying depths depending on the separation of the current and potential electrodes in the survey, and can be interpreted in terms of a lithologic and/or geohydrologic model of the subsurface. Data are termed *apparent* resistivity because the resistivity values measured are actually averages over the total current path length but are plotted at one depth point for each potential electrode pair. Two dimensional images of the subsurface apparent resistivity variation are called *pseudo*-sections. Data plotted in cross-section is a simplistic representation of actual, complex current flow paths. Computer modeling can help interpret geoelectric data in terms of more accurate earth models.

This paper reviews the working ideas behind basic geoelectric methods. In the following sections we present some of the basic resistivity theory, followed by discussions on resistivity field methods and survey geometry associated with the three main surveying techniques: vertical electric sounding (VES), constant separation traversing (CST), and combined sounding and traversing methods. Comprehensive overviews of resistivity methods are presented in Telford (1976), Ward (1990), Kearey and Brooks (1991), and Burger (1992).

BACKGROUND

Ohm's Law

Ohm's Law describes the electrical properties of any medium. Ohm's Law, $V = I R$, relates the voltage of a circuit to the product of the current and the resistance. This relationship holds for earth materials as well as simple circuits. Resistance, however, is not a material constant. Instead, resistivity is an intrinsic property of the medium describing the resistance of the medium to the flow of electric current. Resistivity ($\rho = \delta A \, \delta R / \delta L$) is defined as a unit change in resistance scaled by the ratio of a unit cross-sectional area and a unit length of the material through which the current is passing (Figure 1). Resistivity is measured in ohm-m or ohm-ft, and is the reciprocal of the conductivity of the material. Table 1 displays some typical resistivities. Earth resistivities can range over nine orders of magnitude, from .1-10^8 ohm-m.

Figure 1. Resistivity is defined based on the change in resistance δR for a given change in length δL and cross-sectional area δA of material.

Table 1

Common Resistivities (ohm-m)

Material Value	Resistivity range	Typical
Igneous &	10^2 - 10^8	10^4
Metamporphic rocks		10^3
Sedimentary rocks	10 - 10^8	10^3
Unconsolidated	10^{-1} - 10^4	10^3
Groundwater	1 - 10	5
Pure water		10^3

Note that, in Table 1, the resistivity ranges of different earth materials overlap. Thus, resistivity measurements cannot be directly related to the type of soil or rock in the subsurface without direct sampling or some other geophysical or geotechnical information. Porosity is the major controlling factor for changing resistivity because electricity flows in the near surface by the passage of ions through pore space in the subsurface materials. The porosity (amount of pore space), the permeability (connectivity of pores), the water (or other fluid) content of the pores, and the presence of salts all become contributing factors to changing resistivity. Because most minerals are insulators and rock composition tends to increase resistivity, it is easier to measure conductive anomalies than resistive ones in the subsurface. However, air, with a theoretical infinite resistivity, will produce large resistive anomalies when filling subsurface voids.

Poisson's Equation

The recordings we make in resistivity methods are surface measurements of the potential field distribution due to the current passing through the ground. This potential is a solution to Poisson's equation, ∇^2 P = 0, where ∇^2 is a second derivative operator and P is the potential. For the potential P at a distance r from the current source I on the surface of the earth (an infinite half space below), the solution is given by P = $I\rho/2\pi r$. In reality, a single electrode cannot pass current through a half-space because two electrodes are required to complete the electrical circuit. Also, we do not measure potential, but measure the potential difference between two electrodes. The solution to Poisson's equation for each pair of current and pair of potential electrodes would give a general form for a measured potential difference with electrodes placed anywhere on the surface. In practice, however, the current and potential electrodes are arranged most often in a collinear pattern (Figure 2).

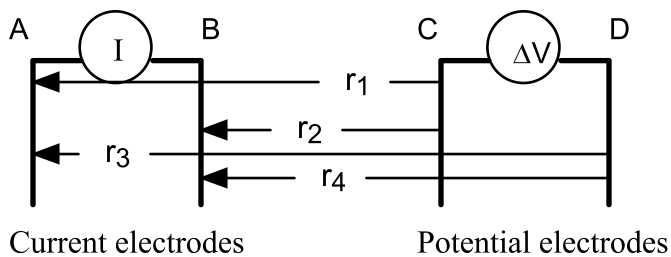

Figure 2. Geoelectric survey with current and potential electrodes collinear.

The resulting equation for the measured potential (voltage) difference is

$$\Delta V = \frac{I\rho}{2\pi}\left[\left(\frac{1}{r_1} - \frac{1}{r_2}\right) - \left(\frac{1}{r_3} - \frac{1}{r_4}\right)\right].$$

By solving the above equation for ρ, we can determine the resistivity of the subsurface region. We derive the above equation assuming a homogeneous and isotropic half-space. Because the earth is neither homogeneous nor isotropic, a measured voltage difference yields a resistivity value that is an average over the path length the current follows. Thus, we can determine only apparent resistivity, given by

$$\rho_a = \frac{2\pi\Delta V}{I}\left[\frac{1}{\left(\frac{1}{r_1} - \frac{1}{r_2}\right) - \left(\frac{1}{r_3} - \frac{1}{r_4}\right)}\right] = \frac{\Delta V}{I}G(r).$$

G(r) is a geometric factor and is dependent upon the spatial arrangement of electrodes for specific arrays.

DC Resistivity

The preceding discussion implies D.C., or zero-frequency current (no reactance). Electrode polarization can occur whenever the mode of current conduction changes from ionic (subsurface) to metallic (electrode). Because energy is required to cause the current to flow across the subsurface/electrode interface, a barrier is established which causes an electrical impedance (Ward, 1990). This barrier is generally composed of mobile ions and acts as an insulator. By alternating the polarity of the induced current, mobile ions do not build up excessively around the electrode and the electrode polarization is minimized. Thus the use of an alternating current source decreases the effect of natural earth potentials that can affect the voltage measurements. So, alternating currents are used in most surveys in order to alleviate noise and measurement problems associated with direct current.

SURVEY DESIGN

Three categories of field techniques exist for conventional resistivity analysis of the subsurface. These techniques are vertical electric sounding (VES), constant separation traversing (CST), and combined procedures which utilize characteristics of both VES and CST.

Vertical electric sounding

Vertical electric sounding (VES) employs collinear arrays designed to output a 1-D vertical apparent resistivity versus depth model of the subsurface at a specific observation point. In this method a series of potential differences are acquired at successively greater electrode spacings while maintaining a fixed central reference point. The induced current passes through progressively deeper layers at greater electrode spacing. The potential difference measurements are directly proportional to the changes in the deeper subsurface. Apparent resistivity values calculated from measured potential differences can be interpreted in terms of overburden thickness, water table depth, and the depths and thicknesses of subsurface strata. The two most common arrays used for VES are the Wenner array and the Schlumberger array.

In the Wenner array configuration, potential electrodes are nested within the current electrodes with a common lateral distance between adjacent electrodes called the electrode *a*-spacing (Figure 3). For sounding measurements, the electrodes in a Wenner array are expanded about a center point by equally incrementing the *a*-spacing. The current therefore progressively passes into deeper layers, with the nominal depth of investigation being equal to the a-spacing. This procedure provides apparent resistivity values that are dependent upon vertical conductivity variations of the subsurface. The geometric factor for the Wenner array is $G(r) = 2 \bullet a$, and this simplicity of algebraic form as well as in-field set-up is part of this array's appeal. The Wenner array generally provides for high signal-to-noise ratios, good resolution of horizontal layers, and good depth sensitivity. Conversely, the Wenner array is not good at determining the lateral location of deep inhomogeneities (Ward, 1990) because the large *a*-spacing degrades lateral resolution, and the potential electrodes are located within the spread of the current electrodes. It is possible to perform limited profiling with the Wenner array by keeping the *a*-spacing constant and moving the entire array laterally between resistivity readings. However, investigation depth and resolution are limited for the profiling Wenner array if the *a*-spacing is held constant throughout the entire survey.

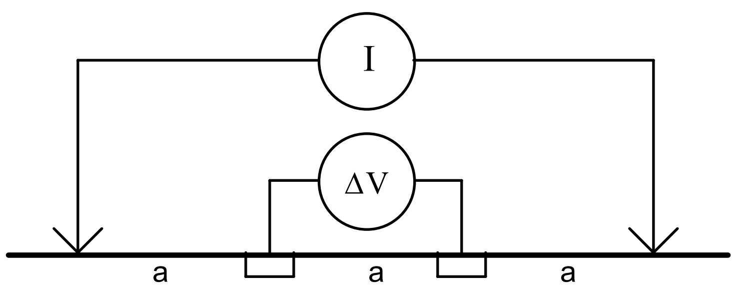

Figure 3. Wenner array. depth of sounding controlled by distance a, or a-spacing.

The Schlumberger array is similar to the Wenner array with respect to having a nested electrode configuration except the potential electrodes have an internal spacing of *a* and the current electrodes are spaced an increased distance of *na* from the potential electrodes, where the integer value *n* varies dependent upon target size and depth. The geometric factor is $G(r) = \pi n(n+1)a$, which can be shown to be just a modification of the Wenner array result. The Schlumberger array of electrodes provides for high signal-to-noise ratios, good resolution of horizontal layers, and good depth sensitivity (Ward, 1990). The Schlumberger technique is somewhat easier to use than the Wenner technique because only two of the four electrodes are moved between successive readings. As an example, we can conduct a Schlumberger VES survey by keeping the potential electrodes fixed at one location while the current electrodes are expanded about a center point. Only when the current electrodes become relatively distant does the potential electrode spacing need to be expanded in order to have measurable potentials.

Constant separation traversing

Electrical profiling, known as constant separation traversing (CST), uses collinear arrays to determine lateral resistivity variations in the shallow subsurface at a more or less fixed depth of investigation. The current and potential electrodes are moved along a profile with constant spacing between electrodes. The two most common array types used for CST are the dipole-dipole and pole-dipole arrays, where a dipole is a pair of current or potential electrodes.

The dipole-dipole resistivity technique consists of a collinear array with current dipole separation of length *a,* potential dipole separation of length *a*, with a total distance between the dipoles of length *na* (Figure 4). Figure 4 also shows where the apparent resistivity value calculated from the measured potential difference is plotted to aid later interpretation. The apparent resistivity value is plotted along intersecting 45 degree lines centered on the dipoles (Hallof, 1957). The geometric factor for the dipole-dipole array is $G(r) = \bullet n(n+1)(n+2)a$. The dipole-dipole technique records the largest anomalies in comparison to other arrays, but its low signal-to-noise ratio limits its applications. Finding small changes in resistivity at great depth would be difficult (Ward, 1990).

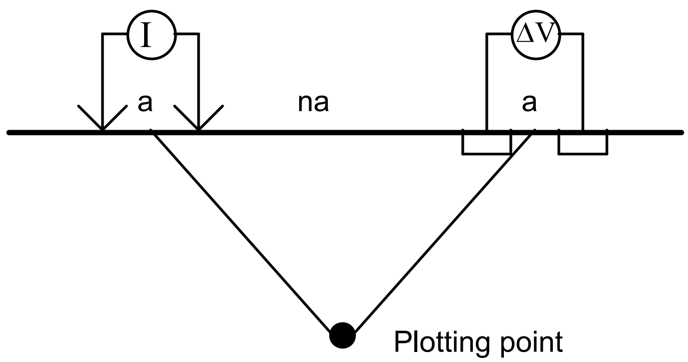

Figure 4. Dipole-Dipole array yields a depth of investigation relative to the value of the integer n which determines the offset between current and potential electrode pairs.

The pole-dipole array has potential electrodes offset from a "single" current source. The single current source actually is a two electrode dipole system with the second electrode (the current sink) placed very far away. The collinear potential electrodes are kept at a constant spacing of *a* and are moved incrementally over intervals of length *a* for distances equal to 10*a* on either side of the local current electrode. By utilizing multiple source locations it is possible to determine depth and size of subsurface anomalies. The geometric factor is derived as $G(r) = 2\bullet n(n+1)a$. The main strengths of the pole-dipole method are its sensitivity to subsurface inhomogeneities and depth of penetration. Weaknesses of the method include low signal-to-noise ratios, insensitivity to dipping structures, and the problems encountered with extensive array lengths (Ward, 1990). The pole-dipole array produces apparent resistivity data similar to dipole-dipole configurations, but associated asymmetry (introduced by the "single" current electrode) decreases lateral resolution. For this reason, the dipole-dipole method of data acquisition has been favored over the pole-dipole method in more recent resistivity studies. Regarding subsurface cavity detection, Spiegel et al. (1980) demonstrated, with the help of modeling software, that the pole-dipole method with 2 meter spacing could detect positive anomalies from 2 x 2 meter air-filled tunnels at depths of 19 meters and 30 meters even over uneven terrain. It is also possible to detect water-filled voids found below the water table by applying the same technique focusing on negative, or low, resistivity anomalies (Smith, 1986). Fountain (1977) demonstrated that the pole-dipole method successfully imaged subsurface cavities, both air- and clay-filled, below roads in Birmingham, Alabama, above mines in Idaho Springs, Colorado, and over complex cave environments at the Southwest Research Institute's Medford Cave Test Site.

Combination of VES and CST

The clear delineation of subsurface anomalies often requires a technique for determining both lateral and vertical features. Three of the previously discussed resistivity arrays (Wenner, Schlumberger, pole-dipole) are capable of performing either lateral measurements (CST) or vertical measurements (VES), but it is generally inefficient for the individual arrays to simultaneously accomplish both sounding and profiling.

A combination VES and CST array, such as a multi-level dipole-dipole array, can overcome the limitations associated with purely profiling or sounding techniques.

The dipole-dipole method has sounding capability as well as profiling applications. By increasing *na* while retaining fixed current electrode locations, multiple potentials may be taken representing greater depth of penetration and increased lateral coverage (Figure 5). In the past, combined sounding-profiling surveys performed with the dipole-dipole method increased *n* from *n*=1,2,3,4 for adequate depth of penetration without introducing spurious noise (Bodmer and Ward, 1968). Now, with the technological advances in resistivity equipment and filtering, multiple levels (up to n=12) can be obtained with reproducible results. The multi-level dipole-dipole technique allows for the efficient acquisition of resistivity values at multiple lateral and vertical locations. For these combined VES/CST surveys, the data are plotted in pseudo-section as apparent resistivity in order to look for anomalous regions. Data are plotted midway between current and potential electrode pairs, associated with varying depths relative to the varying distance between the two active pairs of electrodes (Figure 5).

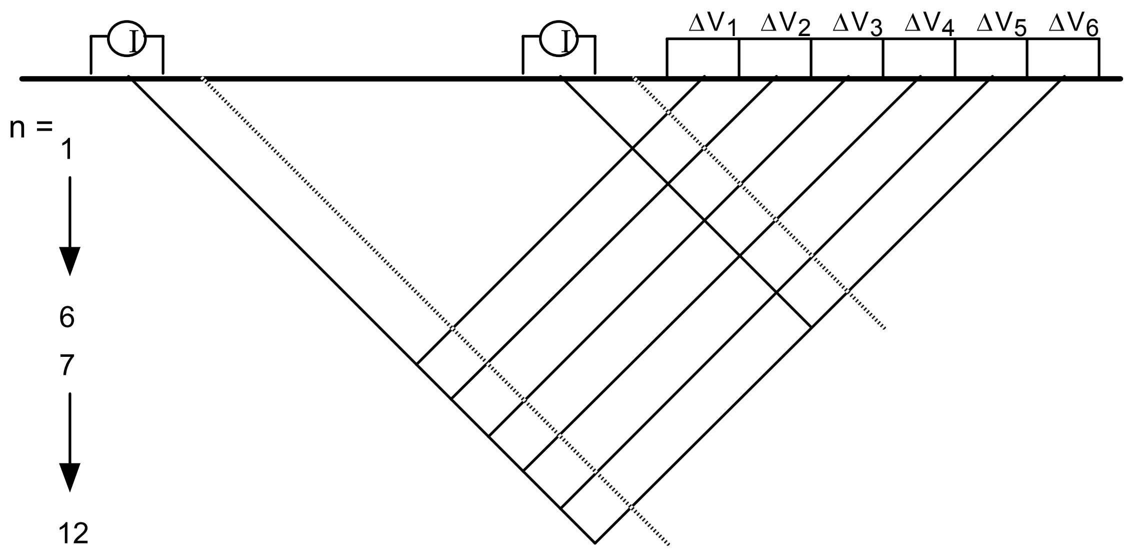

Figure 5. Multi-channel dipole-dipole survey utilizing more than one current electrode pair and multiple potential electrodes in order to conduct a simultaneous VES and CST survey. Data are plotted at intersection of lines from surface dipoles (e.g., along dashed lines as survey continues one step to right).

Azimuthal resistivity

When conducting electrical resistivity surveys with a collinear set of electrodes as described above, most of the current path samples the subsurface below the survey line. We can take advantage of this specific subsurface sampling by varying the azimuth of resistivity surveys in an effort to measure directional variations of electrical properties. This technique can be sensitive to variations in a subsurface that has preferentially aligned fractures. Line azimuths that are perpendicular to water-filled fractures should exhibit higher resistivities, allowing us to map the direction of subsurface fracturing.

3-D and cross-borehole resistivity

Current research is directed toward expanding the applications of resistivity surveying to cross-borehole resistivity tomography and 3-D geometries. The basic concepts for these advanced techniques are the same as for the 1-D and 2-D surveying discussed above; however the details of the survey procedures and analysis techniques can be much more involved. These advanced procedures are not in common practice; however they may become more routine in the near future as recent advances in instrumentation, computer power, and sophistication of computer algorithms allow us to attack these more difficult problems.

ANALYSIS

Interpretation

Because the earth's subsurface is not homogeneous, the electrical properties of the ground (resistivity/conductivity) alter the current density. The equipotential surfaces, perpendicular to the current flow, are modified by the deflection of the electrical current near inhomogeneities. The resistivity method measures the resulting variation in potential differences yielding information about the subsurface inhomogeneity. The measured variations are primarily due to the subsurface material directly below the survey line (in the survey plane), although this is not completely true because the earth is not isotropic. Data are termed *apparent* resistivity because they are averages over a complex current path but are associated with a single depth point in the survey plane. The wide resistivity ranges of earth materials (Table 1) suggest that resistivity data may look noisy. Often data are plotted as the logarithm of the apparent resistivity.

Interpretation of vertical electric sounding data can be as simple as plotting the measurements with respect to some parameter describing the expanding spread (e.g., the increasing *a*-spacing for the Wenner array), and then comparing sounding curves from different areas or different azimuths (Figure 6). We can perform a more detailed analysis through computer simulation of the data, and comparing the resulting calculations with the measured data (curve matching). This latter technique assumes horizontal layering, which is not too limiting an assumption since VES surveys are not sensitive to lateral variation.

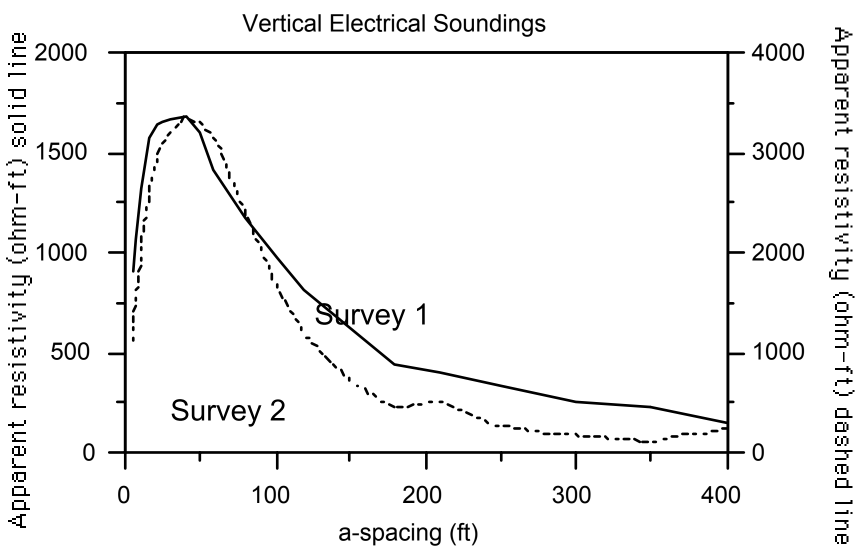

Figure 6. Two VES Wenner array data sets collected with an increasing a-spacing between current and potential electrodes. Note different scale for Survey 1 (left scale) and Survey 2 (right scale). Lower resistivity values are evident for Survey 1, indicating higher conductivity below that survey than nearby at location of Survey 2.

Constant separation traversing is an ideal survey mode for detecting anomalies (Figure 7). Multiple CST surveys can be run along parallel lines, and an anomaly map can be contoured showing the horizontal extent of subsurface features. Resolution of the causative feature is poor, however. Some sort of ground truth, or measurements from another geophysical technique, would be needed to obtain a more quantitative interpretation of the data.

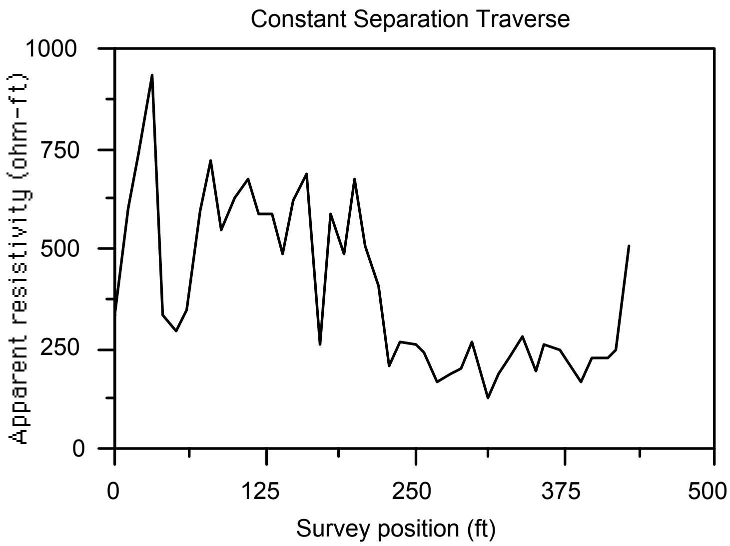

Figure 7. CST dipole-dipole data collected with a constant separation of 10 ft between current and potential dipoles, and a survey step interval of 10 ft. Zone of low resistivity (higher conductivity) is evident on right side of plot.

Combined VES/CST surveys offer the most information (Figure 8). As with CST alone, multiple VES/CST surveys can be planned in order to characterize (image) the vertical as well as horizontal extent of subsurface variations. Images of the subsurface are called *pseudo*-sections because data measurements with respect to depth are only simply represented (Figure 5). Also, caution must be employed when interpreting the pseudo-sections at the sides of the image. The edges (at the ends of the survey) have less data control and are smoothed (extrapolated) estimates of apparent resistivity.

Inversion

Forward modeling can be used to create resistivity models of the subsurface that would simulate apparent resistivities that correlate with the measured data. This procedure is iterative. A starting resistivity model is chosen based on a priori information (from ground truth or averaged geophysical measurements), and apparent resistivity data are modeled for the type of field survey geometry used. These calculated data are compared with the actual data and the resistivity model is updated based on the difference between observed and calculated data. This procedure is continued until the calculated data match the actual measurements to within an interpreter-defined level of error. One of the most important results of inversion is better estimates of depth for cross-section plots, turning pseudo-sections into better approximations of the subsurface variation.

Limitations

The limitations of the resistivity technique include the more difficult interpretation in the presence of complex geology and the existence of natural currents and potentials. The advantages of the resistivity method are the simple theory and methodology. The ability to obtain both sounding data (variations with respect to depth) and profiling data (variations with respect to a horizontal coordinate) is a distinct plus. Data can be obtained and qualitatively interpreted reasonably rapidly, although combined VES/CST surveys will necessarily require more effort than VES or CST alone. Without inversion of the geoelectric data, depths as plotted in pseudo-section are normally an overestimation of the true investigation depth.

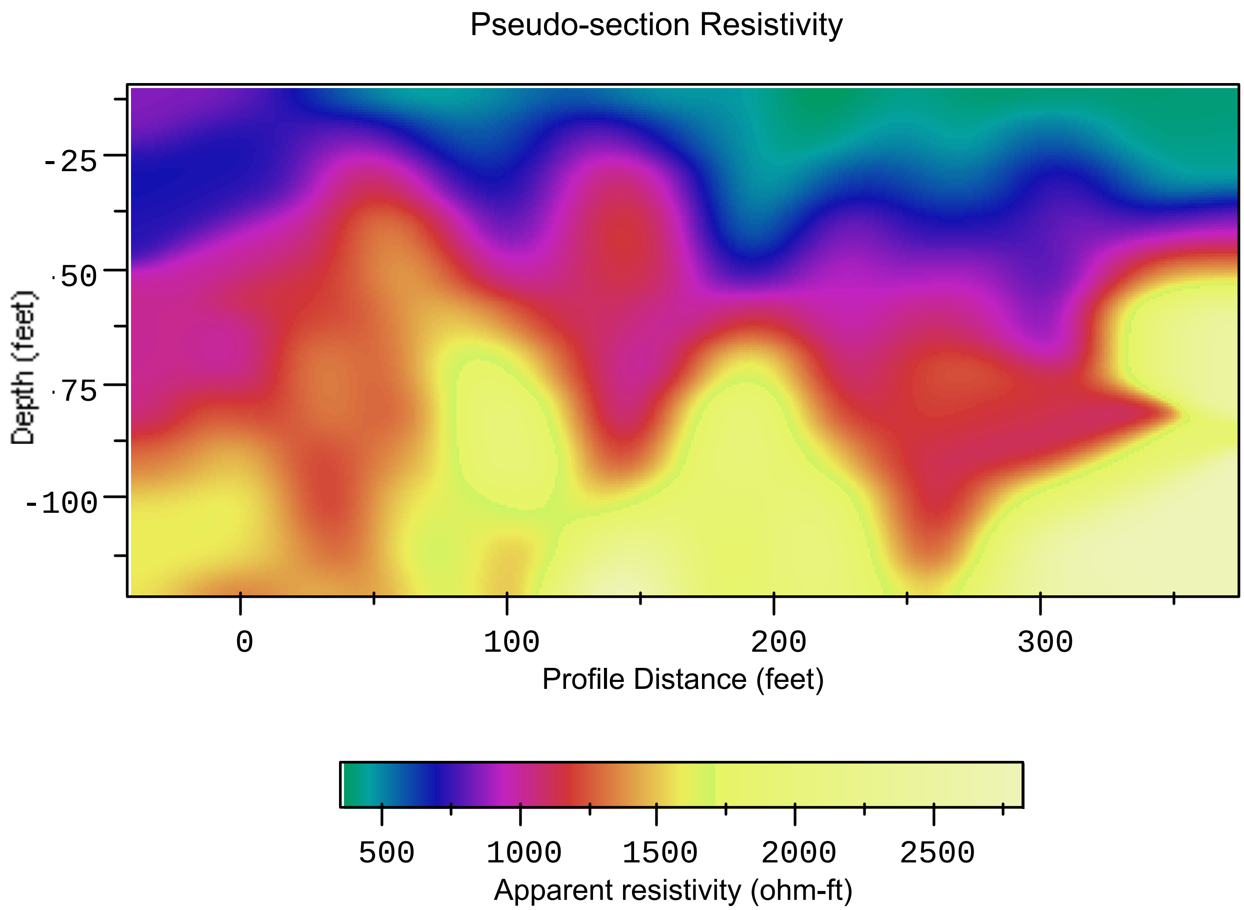

Figure 8. Combined VES and CST resistivity data plotted in pseudo-section. Data were collected with a dipole-dipole multichannel array, with a constant separation of 20 ft between poles in each dipole.

CONCLUSION

Geophysical resistivity techniques are based on the response of the earth to the flow of electrical current. In this method, an electrical current is passed through the ground and two potential electrodes allow us to record the resultant potential difference between them, giving a direct measure of the electrical impedance of the subsurface material. The resistivity, a material constant, is then a function of the measured impedance and the geometry of the electrode array.

In the shallow subsurface, the presence of water controls much of the conductivity variation. Measurement of the resistivity is, in general, a measure of the amount of water saturation and connectivity of pore space. Increasing water content and increasing salinity of the underground water will decrease the measured resistivity. So, increasing porosity of rock and increasing number of fractures will tend to decrease measured resistivity if the voids are water filled. Increasing compaction of soils or rocks will counteract the water-filled porous nature and effectively increase resistivity. Air, with naturally high resistivity, will work opposite to water when filling voids. Whereas the presence of water will reduce resistivity, the presence of air in voids should increase resistivity.

Resistivity measurements at the surface of the earth are associated with varying depths relative to the geometry of the current and potential electrodes in the survey. The apparent resistivity data are routinely plotted as 1-D sounding curves, 1-D profiles, or in 2-D cross-section in order to look for anomalous regions. Computer modeling can be used to help interpret geoelectric data in terms of correct physical earth models. The data can be interpreted qualitatively and quantitatively in terms of a lithologic and/or geohydrologic model of the subsurface.

REFERENCES

Bodmer, R., and Ward, S. H., 1968, Continuous sounding-profiling with a dipole-dipole resistivity array: Geophysics, **33**, 838-842.

Burger, H. R., 1992, Exploration Geophysics of the Shallow Subsurface: Prentice Hall, Inc.

Fountain, L. S., 1977, Detection of subsurface cavities by surface remote sensing techniques: *in* Symposium on Detection of Subsurface Cavities, 12-15 July 1977, Office, Chief of Engineers, U. S. Army, Washington, D. C., and U. S. Army Engineer Waterways Experiment Station Soils and Pavements Laboratory, P. O. Box 631, Vicksburg, MS 39180.

Hallof, P. G., 1957, On the interpretation of resistivity and induced polarization measurements: Cambridge, MIT, Ph.D. thesis.

Kearey, P. and Brooks, M., 1991, An Introduction to Geophysical Exploration: Blackwell Scientific Publications.

Smith, D. L., 1986, Application of the pole-dipole resistivity technique to the detection of solution cavities beneath highways: Geophysics, **51**, 833-837.

Spiegel, R. J., Sturdivant, V. R., and Owen, T. E., 1980, Modeling resistivity anomalies from localized voids under irregular terrain: Geophysics, **45**, 1164-1183.

Telford, W. M., Geldart, L. P., Sheriff, R. E., and Keys, D. A., 1976, Applied geophysics: Cambridge University Press.

Ward, S. H., 1990, Resistivity and induced polarization methods: *in* Geotechnical and Environmental Geophysics, Vol. 1, Ward, S. H., ed: Society of Exploration Geophysicists.